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Locating the solar source of the extremely low-density, low-velocity solar wind flows of 11 May 1999

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Abstract. The solar wind at Earth orbit (1 AU) is known to be strongly supersonic and super Alfvénic with Mach and Alfvén numbers being on average 12 and 9 respectively. Also, solar wind densities (average $\sim 10 \text{ cm}^{-3}$) and velocities (average $\sim 450 \text{ km s}^{-1}$) at 1 AU, are known to be inversely correlated with low velocities having higher than average densities and vice versa. However, on May 11 and 12 1999 the Earth was engulfed by an unusually low density ($< 0.1 \text{ cm}^{-3}$) and low velocity ($< 350 \text{ km s}^{-1}$) solar wind with and Alfvén Mach number significantly less than 1. This was a unique low-velocity, low-density, sub-Alfvénic solar wind flow, which spacecraft observations have shown lasted more than 24 hours. One consequence of this extremely tenuous solar wind was a spectacular expansion of the Earth's magnetosphere and bow shock. The expanding bow shock was observed by several spacecraft and reached record upstream distances of nearly 60 Earth radii, the lunar orbit. The event was so dramatic that it has come to be known as *the solar wind disappearance event*. Our study has shown that the unusual solar wind flows characterizing this event originated from a small coronal hole in the vicinity of a large active region on the sun. These results have put to rest speculation that such events are associated with global phenomenon like the periodic solar polar field reversal that occurs at the maximum of each solar cycle. In this paper we revisit the 11 May 1999 event, look at other "disappearance events" that have occurred in the past, examine the reasons why speculation about the association of such events with global phenomena like solar polar field reversals were made and also examine the role of transient coronal holes as a possible solar source for such events.

Index Terms. Solar wind disappearance, Polar field reversals, Transient coronal holes, Active regions.

1. Introduction

The origin of low-speed solar wind flows has recently been of great interest because, unlike its high speed counterpart that emanates only from large open field regions called coronal holes, the low-speed solar wind can have different origins. Low speed solar wind is known to be associated with small mid-latitude coronal holes and it has been shown that solar wind speeds are inversely correlated with the expansion factors of magnetic flux tubes, with lower speeds coming from regions having large magnetic flux expansion factors and vice versa (Wang and Sheeley 1990, Sheeley et al., 1991). Low-speed solar wind outflows are also known to emanate from the tops of closed coronal loops in helmet streamers, from the outer boundaries of closed loop regions in active regions (Wang et al., 1998), and from small coronal holes in the vicinity of large active regions (Kojima et al., 1999). A high correlation has also been found (Nolte et al., 1976, Neugebauer et al., 1998) between solar wind speed and the size of the coronal hole from which it originates. The extremely spectacular nature of the so-called solar wind disappearance event of 11 May 1999 has caused it to be one of the most extensively studied and reported solar wind related events in recent times. A number of observations have been reported using both space based and ground based instrumentation (Crooker et al., 2000, Farrugia et al., 2000, Richardson et al., 2000, Usmanov et al., 2000, Vats et al., 2001, Balasubramanian et al., 2003, Janardhan, et al., 2005).

Many authors had speculated (Usmanov et al., 2000, Balasubramanian et al., 2003, Usmanov et al., 2003) that the event was somehow related to large scale solar phenomena like the periodic solar polar field reversal and had raised questions about how the solar wind could be turned off for a period of 24 hours or more. Recently, (Janardhan et al., 2005), have been able to locate a solar source of this unusual event and have put to rest speculation about the event being associated with large scale solar phenomena like the periodic solar polar field reversal that takes place at the maximum of each solar cycle.

2. Solar Wind Disappearance Events

Disappearance events are characterized by a long lasting (~ 1 day) and steep drop in the solar wind densities at 1 AU to values significantly less than 1 cm^{-3} . The Alfvén Mach number, which on average is around 9, also drops to values significantly less than unity. The earliest reported case of a disappearance event was that of the long duration density depletion in the interplanetary medium (Schwenn 1983, Gosling et al., 1982), which was observed by Helios 1 and Helios 2 spacecraft. Usmanov et al., (2003) have scanned through the OMNI and ACE spacecraft databases from 1962 to 2002 and have selected those events that have densities of 0.4 cm^{-3} or less and have found a total of 18 such events. Of these 18 events 7, including the 11 May 1999 event during Carrington Rotation 1949 (CR1949), were found to have

minimum density values of 0.2 cm^{-3} or less. Table I shows these seven events from (Usmanov et al., 2003). The last column in Table I is the Alfvén Mach number and it can be seen that all the 7 events are sub-Alfvénic.

Table I. Disappearance Events.

Date	Day No	Rotation	ρ_{\min} (cm^{-3})	Alfvén Mach No
18-10-77	293	1660	0.20	0.79
04-07-79	185	1683	0.10	0.61
31-07-79	212	1684	0.20	0.68
22-11-79	326	1688	0.10	0.54
11-05-99	131	1949	0.02	0.41
20-03-02	79	1987	0.14	0.50
24-05-02	144	1990	0.07	0.54

2.1 The May 1999 Event.

In a detailed and careful study of the disappearance event of 11 May 1999, Janardhan et al., (2005) have carried out, with a reasonable degree of accuracy, the complicated process of tracking the interplanetary event back to the Sun. The authors then identified the 11 May 1999 low density event using *in-situ* data and traced its origin back to a small mid latitude coronal hole, in the vicinity of the large active region complex AR8525 located at around 18-N, and between Heliographic longitudes 280–300° in Carrington rotation 1949 (CR1949). They then showed using potential-field source surface calculations that this location was an open field region with large coronal expansion factor, characteristic of slow solar wind, and that the interplanetary magnetic field was stable and unipolar thereby implying a coronal hole origin for the solar wind flows.

The uppermost panel of Fig. 1 shows a tomographic synoptic velocity map for CR1949 in May 1999 made using IPS observations from the Solar Terrestrial Environment Laboratory (STEL), Toyokawa, Japan. Heliographic longitude is marked at the top of the panel. The map demarcates, by dashed white lines, the locations of the stable, large scale, slow speed flows, $< 400 \text{ km s}^{-1}$. The coronal hole boundaries are demarcated by dashed black lines. The middle panel shows a magnetogram from the SOHO spacecrafts MDI instrument. Regions of large magnetic field strength, corresponding to active region locations are shown as black and white patches to distinguish the two magnetic polarities. The curved solid line is the magnetic neutral line. Converging black lines on the map join magnetic fields on the source surface at $2.5R_{\odot}$ derived from potential field computations (Hakamada and Kojima 1999), with their corresponding counterparts on the photosphere. The potential field lines that are marked in white correspond to fields with CMP date (indicated at the top of the lowermost panel in Fig

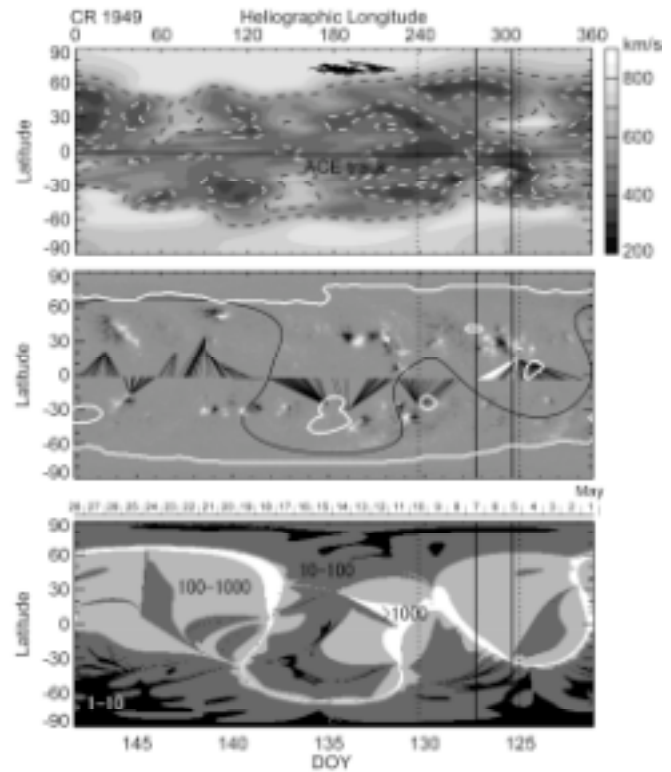


Fig 1. The upper panel shows a tomographic synoptic IPS velocity map projected on the source surface at $2.5 R_{\odot}$. The dashed white and black lines, demarcate respectively, the boundaries of the low velocity flows and polar coronal hole boundaries. The path of the ACE spacecraft is indicated by a thick line along the equator. The middle panel shows a synoptic map made using magnetograms from the MDI instrument on board the SOHO spacecraft. Regions of large magnetic field strength, corresponding to active region locations, are shown as black and white patches to distinguish the two magnetic polarities. The curved solid line is the magnetic neutral line. Converging black lines on the map join magnetic fields on the source surface at $2.5R_{\odot}$, derived from potential field computations with their corresponding counterparts on the photosphere. The potential field lines that are marked in white correspond to fields with CMP date (marked at the top of panel 3) of 11 May 1999. Shown by thick white lines are the locations of CH boundaries. The third panel shows a map of the magnetic flux expansion rates with the white, light-grey, dark-grey and black regions corresponding to flux expansion rates of >1000 , between 100-1000, between 10-100 and between 1-10 respectively. The two sets of solid and dashed vertical parallel lines running across all the panels demarcate respectively, the back projected location of DOY 131 when the solar wind flow was highly non-radial

1) of 11 May 1999 and lie within the two solid, vertically oriented, parallel lines that bracket the trace back location of day-of-year 131 (DOY 131) corresponding to 11 May 1999. Also shown by thick white lines are the locations of CH boundaries inferred from HeI 10830 Å observations. The third panel shows a map of the magnetic flux expansion rates with the white, light-grey, dark-grey and black regions corresponding to flux expansion rates of > 1000 , between 100-1000, between 10-100 and between 1-10 respectively. The two sets of solid and dashed vertical parallel lines running across all the panels demarcate respectively, the back projected location of DOY 131 when the solar wind flow was highly non-radial and days on either side of DOY 131 when the solar wind flow was radial. The dashed vertically oriented parallel lines therefore represent the maximum possible errors in the back projected solar source locations. It can be seen from the lowermost panel of Fig 1 that the source region of

the slow solar wind flows (around the region where the converging potential field lines are marked in white in the middle panel of Fig 1) is dominated by large coronal flux expansion factors, between 100-1000, as can be expected of the slow solar wind. Fig 2 shows, as a function of DOY, the

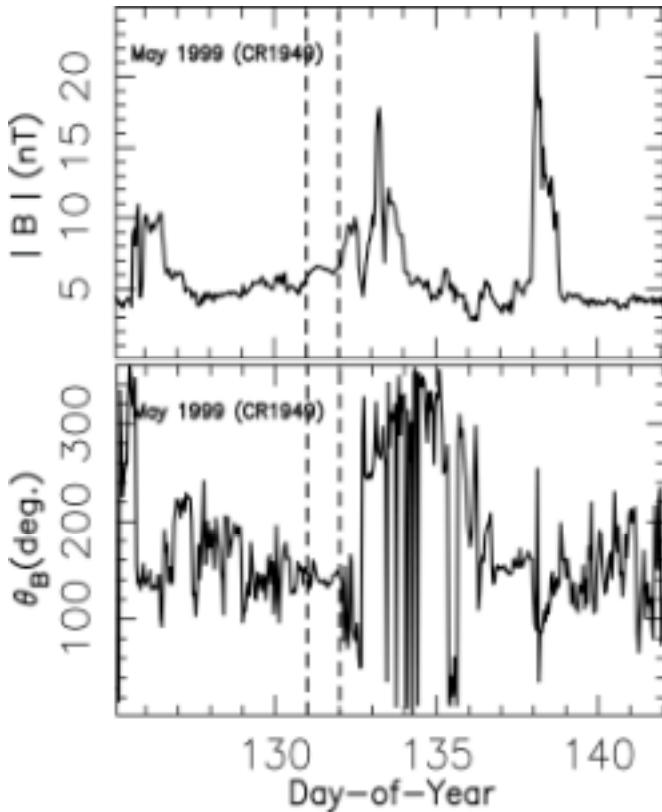


Fig 2. Shows, at 1 AU, the magnitude of the interplanetary magnetic field in nT (top) and the azimuthal direction of the magnetic field in the ecliptic plane as a function of DOY in 1999. The vertically oriented dashed parallel lines in both panels demarcate DOY 131.

magnitude and direction of the interplanetary magnetic field. While the upper panel shows the absolute magnitude in nT of the IMF, the lower panel shows azimuthal direction of the magnetic field in the ecliptic plane. DOY 131 is demarcated in Fig 2 by two vertically oriented dashed parallel lines. It can be seen from the figure that the magnitude of the magnetic field shows hardly any fluctuations during DOY 131 and the direction of the field remains constant. This is in contrast to other days when the direction of the field shows large and rapid changes (c.f. DOY 138). The low variance in the magnitude of the magnetic field and the lack of change in the actual direction of the magnetic field indicate that the solar wind flow during DOY 131 was stable and unipolar, implying a possibly a coronal hole origin of the solar wind flow of 11 May 1999. The upper panel of Fig. 3 shows a map of the solar photosphere on 5 May 1999 indicating the location of active region AR8525 by an arrow. The lower panel shows, as viewed from 315° in Carrington longitude, the three-dimensional potential field structure of the coronal magnetic fields for CR1949 on 5 May 1999 with the black and grey lines denoting the outward and inward magnetic polarities, respectively. The field lines, plotted only between 5 G and 250 G on the photosphere, are shown projected on to the source surface at $2.5 R_\odot$. The thick curved line in the

lower panel is the magnetic neutral line. It is apparent from Fig 3 that AR8525 was at central meridian on 5 May 1999, implying earth directed outflows and that the region was dominated by a large open flux configuration going out into the interplanetary medium.

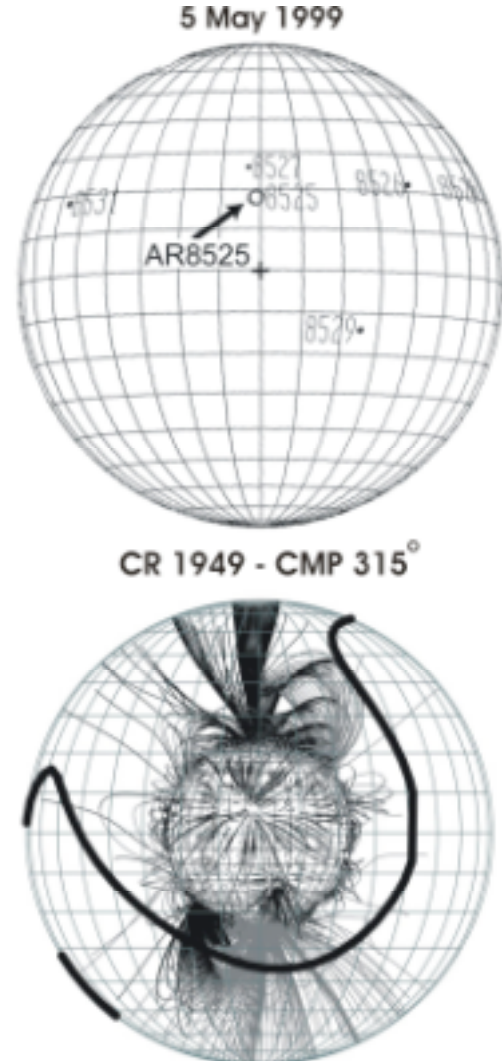


Fig 3. The upper panel is a map of the solar photosphere on 5 May 1999 indicating the locations of the large active regions. The location of AR8525 is shown by an arrow. The lower panel shows the three-dimensional potential field structure of the coronal magnetic fields for CR1949 on 5 May 1999. The image is shown as viewed from 315° in Carrington longitude. The black and grey lines denote the outward and inward magnetic polarities, respectively, and are shown projected on to the source surface at $2.5 R_\odot$. The thick curved line in the lower panel is the magnetic neutral line.

2.2 The Events of March and May 2002.

An important aspect of the disappearance event of 11 May 1999 was that the solar wind flows were highly non-radial. ACE measurements have shown that the deviations from radial flow of the solar wind on DOY 131 was such that the azimuthal component of the solar wind velocity went as high as 100 km s^{-1} . Under these circumstances, solar source locations computed by a trace-back technique using constant velocities along Archimedean spirals would be expected to have large errors. However, Janardhan, et al., (2005) have

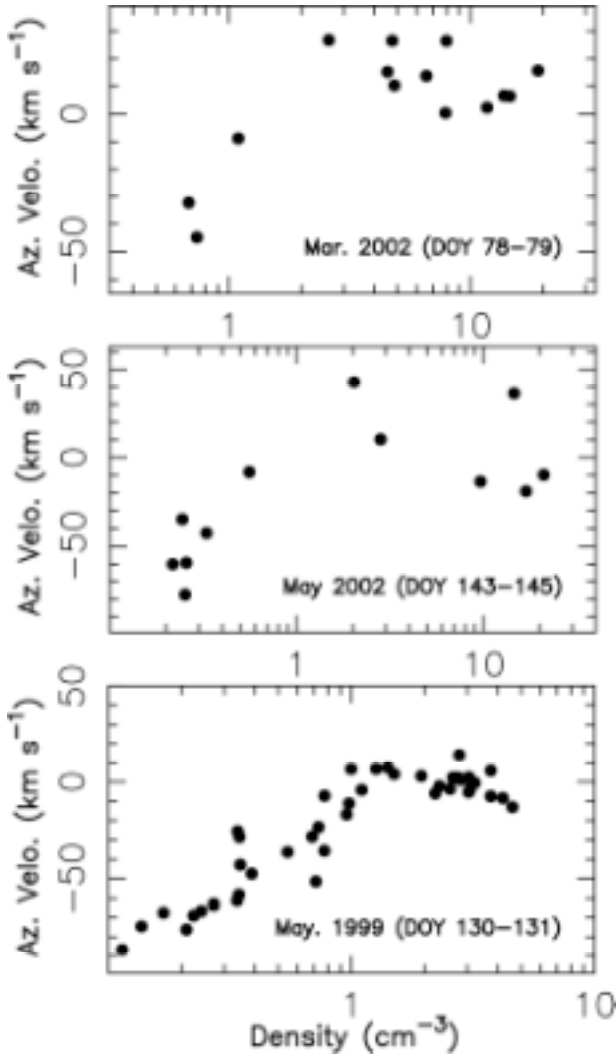


Fig 4 Plots hourly averages of the variation of proton density as a function of the azimuthal component of the solar wind velocity for the three disappearance events of March 2002 (upper panel), May 2002 (middle panel) and May 1999 (lower panel)

shown that the Alfvén radius, R_A (the distance to which the solar wind co-rotates with the Sun), which is normally a function of both the density and the magnetic field, became independent of the magnetic field during this event causing the Alfvén radius to extend outwards by a factor of ~ 5 times from its normal. Using this fact (Janardhan, et al., 2005) have computed the trace-back errors and have shown that the large azimuthal velocities observed during the 11 May 1999 event would not produce very serious errors in the source locations determined by the constant velocity trace-back technique.

Of the three disappearance events that took place in solar cycle 23, two took place in March and May 2002 during Carrington rotations CR1987 and CR1990 respectively. It is instructive to compare these two events with the event of 11 May 1999. Fig. 4 shows the variation of the azimuthal component of the solar wind velocity as a function of density for the disappearance events of March 2002 (upper panel),

May 2002 (middle panel) and May 1999 (lower panel). The densities and velocities are hourly averages measured by the ACE SWEPAM instrument onboard the SoHO spacecraft. It is clear from Fig 4 that as the density decreases, the azimuthal or westward flow deviation of the solar wind increases. This anti-correlation is most apparent in the data of 11 May 1999 and implies that during the disappearance event, the Alfvén radius becomes independent of magnetic field. Fig 5 and Fig 6 show respectively (In a manner similar to Fig 2) the magnitude and direction of the interplanetary magnetic field for the disappearance events of March 2002 and May 2002 as a function of DOY. While the upper panels in both Fig 5 and Fig 6 shows the absolute magnitude, in nT, of the IMF the lower panel shows the azimuthal direction of the magnetic field in the ecliptic plane. It can be seen from

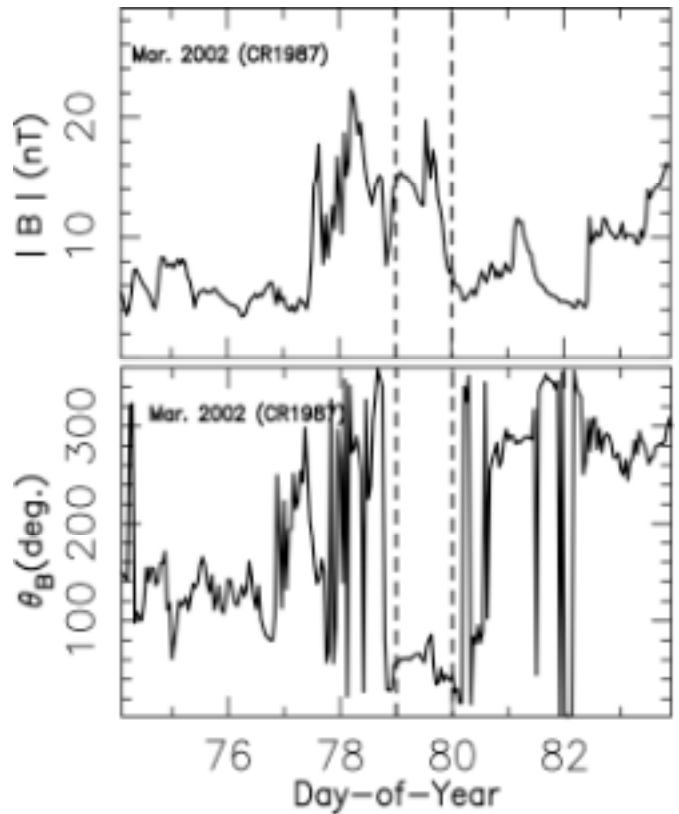


Fig 5. Shows, at 1 AU, the magnitude of the interplanetary magnetic field in nT (top) and the azimuthal direction of the magnetic field in the ecliptic plane as a function of DOY in 2002. The vertically oriented dashed parallel lines in both panels demarcate DOY 79 in March 2002.

Fig 5 that the magnetic field shows a low variance and is stable and unipolar through the first half of DOY 79 for the event of March 2002 and the magnetic field is stable and unipolar during DOY 144, for the event of May 2002. Fig 7

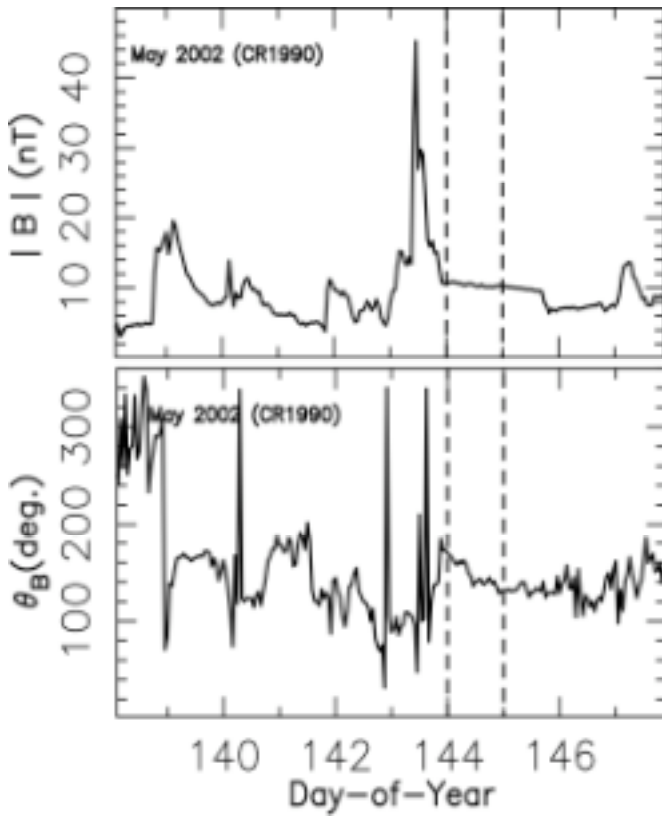


Fig 6. Shows, at 1 AU, the magnitude of the interplanetary magnetic field in nT (top) and the azimuthal direction of the magnetic field in the ecliptic plane as a function of DOY in 2002. The vertically oriented dashed parallel lines in both panels demarcate DOY 144 in May 2002.

shows by filled circles joined by a dashed line, hourly averages of ACE spacecraft measurements at 1 AU of proton density as a function of DOY for the March 2002 (upper panel), May 2002 (middle panel) and May 1999 events (lower panel) respectively. It can be seen from Fig 7 that the densities remained low for about half a day during DOY 79 before beginning to rise again for the event of Mar 2002. For the May 2002 event, the densities remained low for the whole of DOY 144 and for the event of May 1999 the densities continued to drop through the whole of DOY 131 and remained below 1 particle cm^{-3} for over 24 hours. Fig 8 shows ACE measurements of velocities as a function of DOY for the same three events. It can be seen that while the densities drop steeply in all three events to the minimum values as indicated in Table I, the velocities show a steep drop that is correlated with the drop in density, only in the 11 May 1999 event. As stated earlier, solar wind densities (average $\sim 10 \text{ cm}^{-3}$) and velocities (average $\sim 450 \text{ km s}^{-1}$) at 1 AU, are known to be inversely correlated with low velocities having higher than average densities and vice versa. It can be seen that this is indeed the case for the events of March

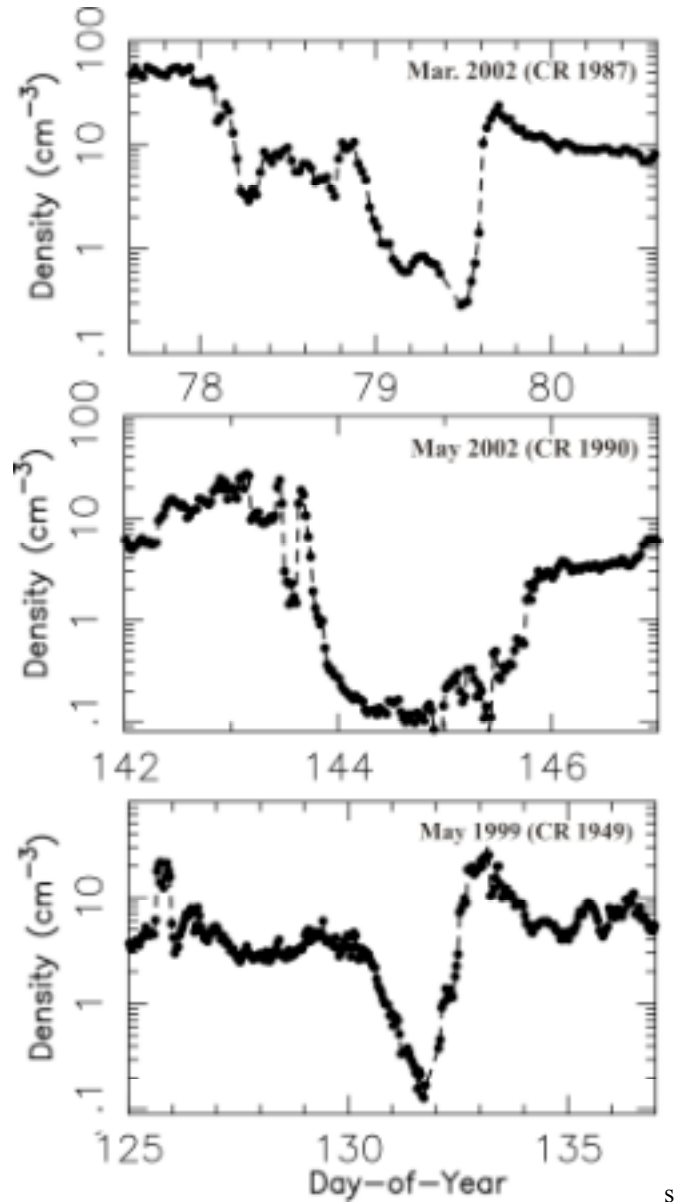


Fig 7 Shows plots of proton density, measured by the ACE SWEPAM instrument at 1AU as a function of Day-of-Year for the disappearance events of Mar 2002 (DOY 79 – upper panel), May 2002 (DOY 144 – middle panel) and May 1999 (DOY 131 – lower panel). The Carrington rotation in which the events occurred is indicated in each panel.

and May 2002 while in the May 1999 event both densities and velocities show a simultaneous and steep drop, thus making the associated solar wind flow of May 1999 unique and unusual.

4. Discussion and Conclusions

While the large magnetic flux expansion factors and the small size of the coronal hole associated with the event of May 1999 could explain the low velocities seen, the extremely low densities observed cannot be so easily explained. Janardhan, et al., (2005) have proposed an interesting method for producing the low densities, by

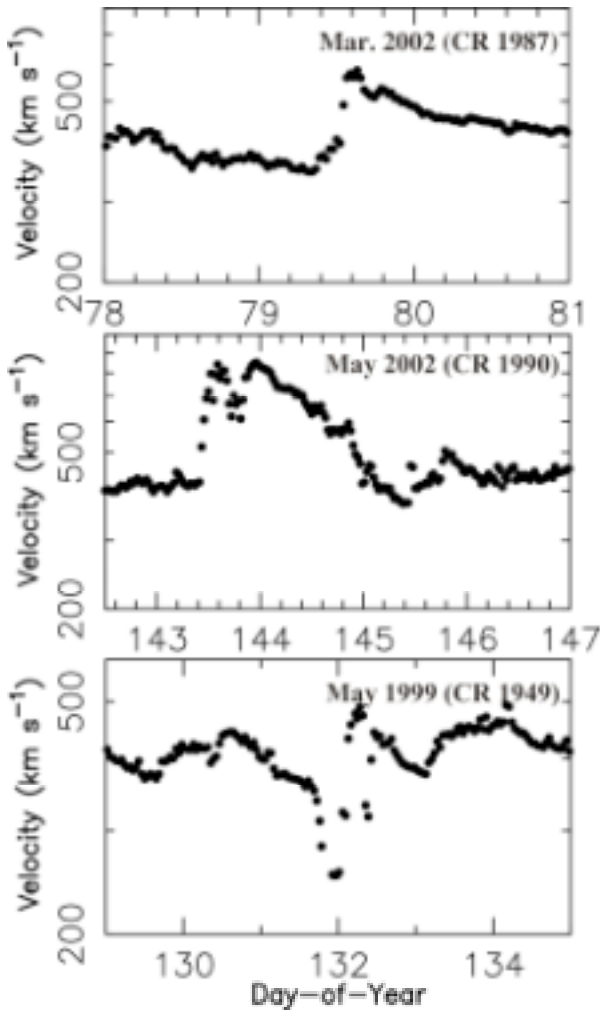


Fig 8. Shows the solar wind velocity measured by the ACE SWEPAM instrument as a function of Day-of-Year (DOY) for the three solar wind disappearance events in March 2002 (DOY 79 – upper panel), May 2002 (DOY 144 – middle panel) and May 1999 (DOY 131 – lower panel) respectively. The Carrington rotation in which the events occurred is indicated in each panel.

assuming that rearrangements in CH boundaries would produce a pinch-off or separation of the solar wind outflow, thereby completely detaching the outflow from its solar source. They have argued that if such a detached outflow occurred within 48 hours of its start and it continued to expand as it propagated out to 1 AU, an increase in its radius by a factor of 6-7 would lead to a decrease in densities by a factor of 200-300 at 1 AU. Thereby, typical particle densities of approximately $20\text{--}30 \text{ particles cm}^{-3}$ at 0.5 AU could be reduced to $0.1 \text{ particles cm}^{-3}$ at 1 AU given that the typical travel time between the sun and the earth, at these low velocities, is ~ 5 days. In light of the arguments put forward by Janardhan *et al.*, (2005) it is interesting to ask if there could be any other candidates, apart from small mid latitude coronal holes that could cause such low density, low velocity solar wind flows at 1 AU?

Apart from small mid latitude coronal holes, another class of coronal holes is the so-called transient coronal holes (TCH), which were first discovered in Skylab data (Rust 1983). These TCH are short lived (~ 2 days) regions of dimmed X-

ray intensity, which are sometimes observed in association with CME's. In an extensive study of 19 TCH, using 9 years of data from the YOHKOH soft X-ray telescope (SXT), (Kahler and Hudson 2001) have shown that TCH are:

1. are small in size
2. occur in magnetic unipolar regions trailing large active regions
3. generally occur in regions where the magnetic neutral line shows large scale curvature
4. have short lifetimes, typically about ~ 48 hours

From the above it is clear that TCH could also be very good candidates for causing disappearance events. Their short lifetimes of ~ 48 hours when compared with the typical travel times between the Sun and 1 AU of 3–5 days for the solar wind would imply that outflows originating at a small TCH can become totally disconnected from the source. However, one problem with detecting TCH is that the coronal radiation responsible for HeI 10830 Å would come from higher altitudes than soft X-ray emission and thus represent large spatial scales. HeI 10830 Å observations of coronal hole boundaries will therefore be blurred and cannot be used to detect the smallest TCH, which are generally small in size. Even at soft X-ray wavelengths, since the corona is optically thin, foreground and background emission can prevent the detection of TCH on the limb thereby limiting TCH detections to those that are well away from the limb. Thus, detecting TCH would require special and careful processing of soft X-ray and EUV data.

The stable and unipolar nature of the flows from the vicinity of AR8525, the central meridian location of AR8525 taken together with the extensive and detailed work by (Kahler and Hudson 2001) described above indicate that transient coronal holes could be an alternative solar source for explaining other such low velocity, tenuous solar wind flows seen at 1 AU. From Figure 1 (upper panel) we can see that the solar wind flows of 11 May 1999 originated from a small area on the sun trailing AR8525 and the magnetic neutral line showed a large curvature. It is therefore not unreasonable to speculate that the other tenuous solar wind outflows listed in Table 1 could have probably have probably originated in small TCH. The small area of the TCH associated with such an outflows would produce very low velocities (Wang and Sheeley (1990), Sheeley *et al.*, 1991, Nolte *et al.*, 1976), Neugebauer *et al.*, 1998). The typical lifetime of a TCH of ~ 2 days as compared to solar wind travel time of ~ 5 days would imply that the low velocity flow from the TCH would have been completely detached from the solar surface approximately three days before reaching 1 AU and after propagating roughly 40% of the distance to earth orbit. As described earlier a simple expansion of this large detached low velocity flow region, as it propagated out to 1 AU, could give rise to an extremely low density cloud that engulfs the earth.

From an analysis of the three disappearance events carried out it is apparent that stable and unipolar outflows from the Sun were responsible for all three events described. It is very interesting to note that the Alfvén radius in all events

becomes independent of the magnetic field. From fig 4 we can see that the azimuthal component of the solar wind velocity went as high as 100 km s^{-1} for the disappearance event of May 1999 and it went to $\sim 50 \text{ km s}^{-1}$ for the two events of March 2002 and May 2002. If we therefore assume that this azimuthal velocity component (V_a) was due to co-rotation of the solar wind out to a distance corresponding to the Alfvén radius (R_A), then R_A can be computed since $R_A \Omega_\odot = V_a$ where, $\Omega_\odot = 1.642 \times 10^{-4} \text{ deg s}^{-1}$ is the angular speed of the Sun. Thus R_A could extend outwards from its normal location of $\sim 0.05 \text{ AU}$ to as much as 0.23 AU for the May 1999 event and out to 0.11 AU for the two events in March and May 2002. Thus R_A can extend outwards by a factor of 2-5 during a disappearance event.

Four of the events listed in Table 1 have occurred close to the solar maximum while the remaining have occurred well within two years of the maximum when solar activity was still high. This fact, viz. disappearance events seemed to occur at or around solar maximum when the Sun was undergoing a polar field reversal led many authors to speculate (Usmanov et al., 2000, Balasubramanian et al., 2003, Usmanov et al., 2003) that the large-scale restructuring of the solar magnetic fields during solar polar field reversals, is likely to be associated with density anomalies in the solar wind. The current work indicates that at least in the case of the 11 May 1999 event, the connection with polar field reversal periods is incidental in that the solar maximum period is dominated by large active regions and a highly deformed neutral line configuration, thereby maximizing the likelihood for the formation of small TCH (Kahler and Hudson 2001) and/or small mid latitude CH. Also mid latitude and equatorial coronal holes are nearly absent during the solar minimum phase thereby increasing the likelihood of such events being observed only at or around solar maximum. Finally, spacecraft observations are confined to the ecliptic, another reason for observing such events at or around solar maximum because of the increased probability for the occurrence of mid-latitude and equatorial coronal holes during solar maximum. A more detailed study of the two disappearance events of March and May 2002 will be required to see if the source locations of the associated low density flows can be determined.

Since coronal hole boundaries locate separatrices of coronal magnetic fields, which in turn define its large-scale current systems, this work has also highlighted the need for systematic studies of the dynamics and evolution of CH boundaries. Such studies could help define coronal hole boundary structure and help in understanding boundary field connectivity's. Regular and systematic observations by both ground and space based platforms will be required to identify many more such events and ground based IPS observations will be of value in such future studies.

5. Acknowledgements

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